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CNRS

Tuning of Musical Glasses through material removal

Accord de verres musicaux par retrait de matière

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Musical Glasses and Tuning Process

The *Glasharfe*

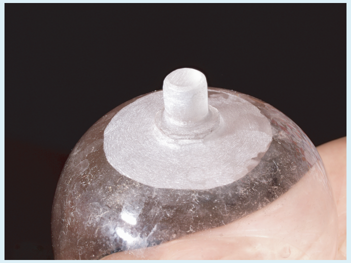
- Built in 1976 by german virtuoso *Bruno Hoffmann* (1913-1991)
- formed by 50 stem glasses of 4 different diameters
- hand-made, blown leadless cristal
- spans nearly 4 octaves (D_2 to C_6), chromatic
- A_3 at about 446Hz

The instrument is played by the performer gently revolving his (lightlty moist) fingers around the rim of the glasses.

Tuning

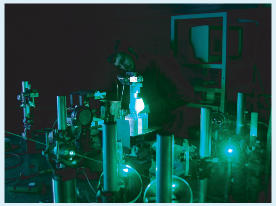
The instrument maker chooses from a set of hundreds of glasses of different sizes the 50 glasses that are the closest to the desired tones.

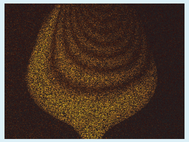
If needed, the glasses are then fine-tuned by removing material near the stem (see picture). According to the maker, the pitch can be lowered to about a half tone by this manner.



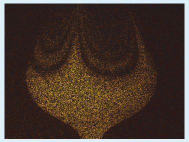
This tuning process awaked our interest and is the subject of this study.

Vibrational Modes



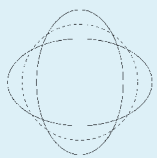


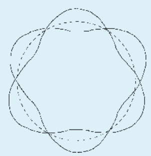
710Hz (n=2)



1420Hz (n=3)

Using speckle interferometry, the vibrational modes of the musical glasses can be shown.

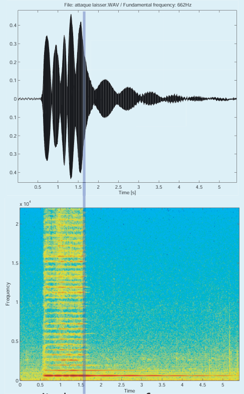




When the glass is excited by a rotating finger, the excited circonferential mode is (n=2).

Spectral Analysis

Low-Frequency Amplitude Variation



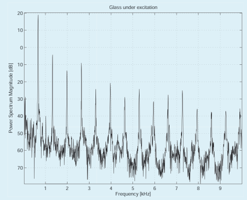
The frequency of this modulation is different when the glass is excited (left side) or let free (right side of the plot).

- During the excitation, the beating is caused by the fact that the rotating finger imposes a rotating node, resulting in a mobile source effect (the beating frequency corresponds to the rotation frequency of the finger).

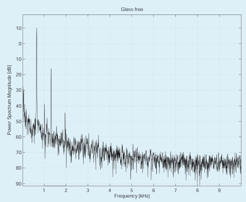
- In free mode, the beating is caused by the interferences between travelling waves along the glass rim.

Regular Harmonics

The richness in harmonics of a musical glass is surprising (given the perceived purity of its sound) and the observed spectra cannot be fully explained yet.



excited



free

Again, a difference is observed between the excited and free situations. The spectrum of an excited glass shows a great number of harmonics, that quickly disappear when the glass is let free.

This is due to the fact that the higher frequency components are damped more quickly than the others in the absence of an excitation

References

[1] A.P. French. In Vino Veritas: a study of wineglass acoustics. *American Journal of Physics* **51**(8): 688-694, 1983

[2] Ph.M. Morse. *Vibration and Sound*, Chapter 4, pages 151-166. The American Institute of Physics, 1983

[3] K. Oku, A. Yarai and T. Nakanishi. A new tuning method for glass harp based on a vibration analysis that uses a finite element method. *Journal of the Acoustical Society of Japan* **21**(2): 97-104, 2000

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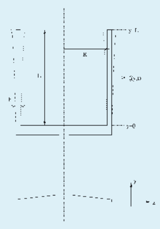
The authors wish to thank Mrs. I. Emge and Mr. J.-F. Zürcher for motivating them to work on the problematic of the tuning of musical glasses.

Analytical and Numerical Models



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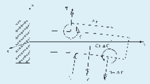


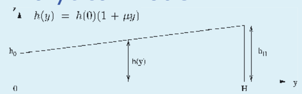
circonferential mode *n*

$$f_{mn} = Kh\sqrt{\frac{(n^2-1)^2+(\beta_m b)^4}{1+\frac{1}{n^2}}}$$

vertical mode *m*

The tuning process affects mostly the vertical modes. So the vibrational modes of a clamped-free beam (generatrix of a cylindrical glass) are studied [1].
The shaving of the glass is approximated by a linear variation of the glass walls' thickness.

Analytical Model



The frequency variation is obtained using the method of small perturbations [2].

Flexion equation of a non-uniform beam:

$$\frac{\partial^4\zeta}{\partial y^4}+\frac{2}{I}\frac{\partial I}{\partial y}\frac{\partial^3\zeta}{\partial y^3}+\frac{1}{I}\frac{\partial^2 I}{\partial y^2}\frac{\partial^2\zeta}{\partial y^2}-\frac{\rho S\omega^2}{EI}\zeta(y)=0$$

Using a linearly variating thickness, considering small perturbations only and approximating to the first order leads to

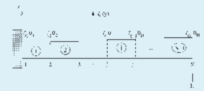
$$\frac{\partial^4\zeta}{\partial y^4}+6\mu\frac{\partial^3\zeta}{\partial y^3}-\gamma^4(y)\zeta(y)=0$$

The resonance frequencies of the non-uniform beam are believed to be near the ones of the uniform beam. The non-uniform modes are seeked in the base spun by the uniform modes. To isolate the wanted term, a projection on one of these uniform modes is used. Finally:

$$f_m = f_{m0}(1+\theta_m)$$

$$\theta_m = \left[2\int_0^L y\zeta_{m0}^2\,\mathrm{d}y - \frac{3}{\gamma_{m0}^4}\left(\frac{\partial\zeta_{m0}}{\partial y}\right)^2_{y=L}\right]\frac{\mu}{L}-K\frac{\mu}{L}$$

Finite Element Model



Flexion equation with an excitation source in y_s:

$$\frac{\partial^4\zeta}{\partial y^4}+6\mu\frac{\partial^3\zeta}{\partial y^3}-\gamma_0^4(1-2\mu y)\zeta(y)=\delta(y-y_s)$$

Integration by parts, taking the boundary conditions into account:

$$\int_0^L\frac{\partial^2\nu}{\partial y^2}\frac{\partial^2\zeta}{\partial y^2}\mathrm{d}y - \gamma_0^4\int_0^L\nu\zeta\,\mathrm{d}y + 2\mu\left(-3\int_0^L\frac{\partial\nu}{\partial y}\frac{\partial^2\zeta}{\partial y^2}\mathrm{d}y+\gamma_0^4\int_0^L\nu y\zeta\,\mathrm{d}y\right)=\int_0^L\nu f\,\mathrm{d}y$$

The domain [0..L] is decomposed into *N* elements. On each element, the displacement is sought under a polynomial cubic form. The final equation in matrix form is:

$$\langle\delta\zeta_j,\delta\theta_j,\delta\zeta_{j+1},\delta\theta_{j+1}\rangle[W_e(\omega,\mu,y_j)]\begin{Bmatrix}\zeta_j\\ \theta_j\\ \zeta_{j+1}\\ \theta_{j+1}\end{Bmatrix} = \langle\delta\zeta_j,\delta\theta_j,\delta\zeta_{j+1},\delta\theta_{j-1}\rangle\{f_e\}$$

The resonance frequencies are obtained by sweeping and searching for maxima.

Caution must be given to the fact that approximations have been taken on multiple levels (1st order approximation in the equation and in the tratment for the analytical model, 3rd order polynomial approximation for the finite element model).

Results

The computed results are compared to experimental data [3].

Both models confirm the preponderance of the vertical modes in the tuning process.
To obtain a reduction of the pitch of a half tone (approx. 6%), a thickness reduction of at least 3% is necessary.